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COMPUTATIONAL SIMULATION OF PROPULSION STRUCTURES PERFORMANCE AND RELIABILITY

Dale A. Hopkins
NASA Lewis Research Center
Cleveland, Ohio

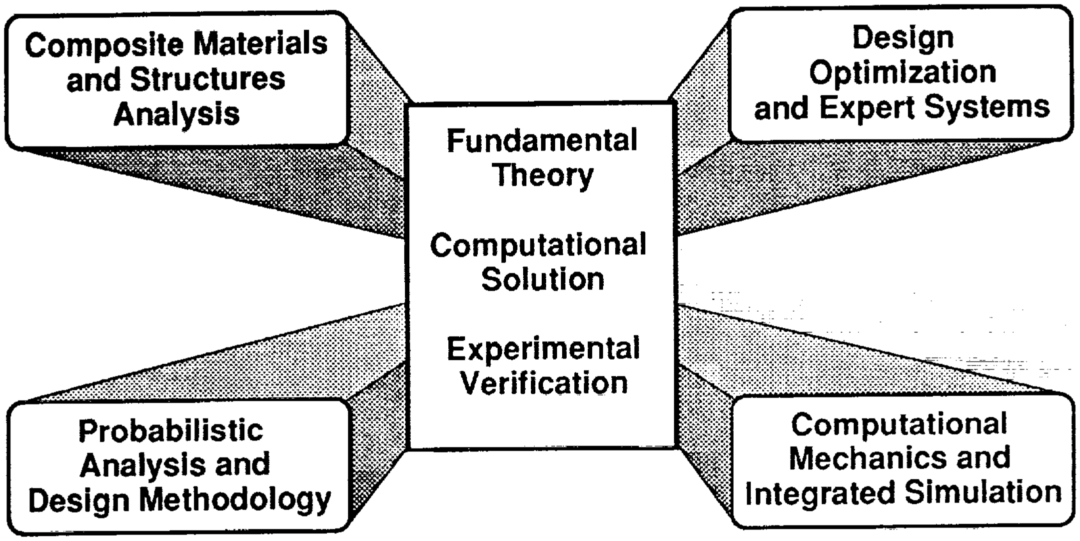
The chronicle of aeropropulsion development reveals a deliberate evolution during which new engine designs have been derived by incremental improvements on successful previous systems. Aerospace vehicles envisioned near the turn of the century and beyond demand advances in propulsion systems of more revolutionary than evolutionary significance. The systems of tomorrow will require unprecedented levels of performance, durability, reliability, and operational economy. Achieving these requirements presents a significant challenge to develop enabling computational structures technology.

An onerous consequence now endured because of deficient analysis and design capabilities is the reliance on hardware tests to demonstrate and certify engine system requirements. Indeed, a considerable amount of the total time and cost associated with developing a new engine can be attributed to the several iterations that typically occur in the design-build-test cycle. Alleviating the dominance of hardware tests can substantially reduce the time and cost of propulsion development. The aim of computational structures technology is to transform the engine development process by empowering computational simulation to have the principal role.

The arena of computational structures technology for aeropropulsion has produced some noteworthy recent gains, and even more extraordinary advances are still to be realized. The essential elements in this endeavor are (1) fundamental theoretical models that more completely represent the complex physics governing engine structural performance, (2) computational techniques that provide accurate and efficient solutions of the governing models and which exploit the potential of emerging computer technology, and (3) integrated strategies for simulation that allow engine structural models of varying fidelity to be evaluated as a continuous and adaptive process.

The obvious benefit of the new capabilities that are being pursued is a greater opportunity to examine alternative concepts or to address other issues that are pertinent to engine system design. More profoundly, the new capabilities can be utilized to address major obstacles that are now only confronted through hardware testing. These efforts promise a new potential that inevitably will stimulate ideas for overcoming future propulsion barriers. Success in these endeavors will contribute to an ideal of "computation to flight" for aerospace propulsion systems. It is this ideal that inspires the research and development of computational structures technology at Lewis Research Center.

Computational Structures Technology Development is Broad Based and Comprehensive



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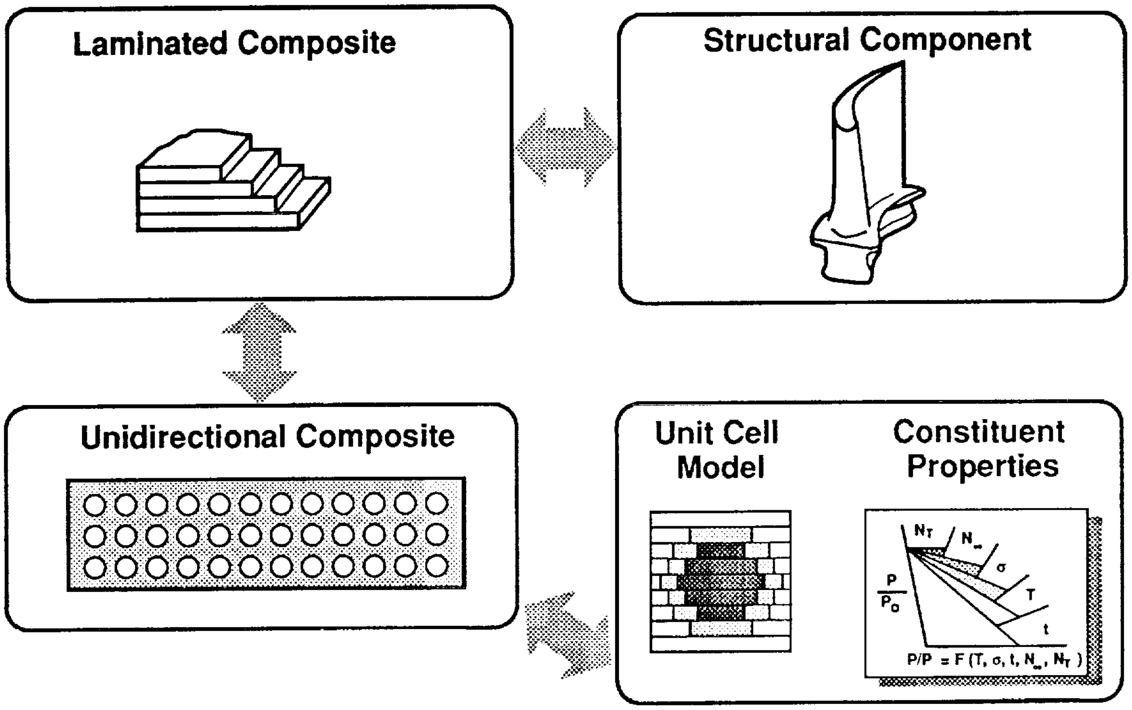
This presentation gives a partial overview of research and development efforts underway in the Structures Division of Lewis Research Center, which collectively can be referred to as the computational structures technology program. The efforts in the program are diverse and encompass four major categories: (1) composite materials and structures, (2) probabilistic analysis and design methods, (3) design optimization and expert systems, and (4) computational methods and integrated simulation. The approach of the program is comprehensive and entails (1) exploration of fundamental theoretical models of structural mechanics that more completely represent the complex physics governing engine structural performance; (2) formulation and implementation of computational techniques and integrated simulation strategies that provide accurate and efficient solutions of the governing theoretical models by exploiting the potential of emerging computer technology, and which allow engine structural models of varying fidelity to be evaluated with arbitrarily specified resolution as a continuous and adaptive process; and (3) validation and verification through numerical and experimental tests to establish confidence and define the qualities and limitations of the resulting theoretical models and computational solution methods. The program comprises both in-house and sponsored research activities. The remaining pages provide a sampling of the activities to illustrate the breadth and depth of the program and to demonstrate the accomplishments and benefits of the program.

Multiscale Approach Relates Local Effects to Global Behavior of Composite Structures



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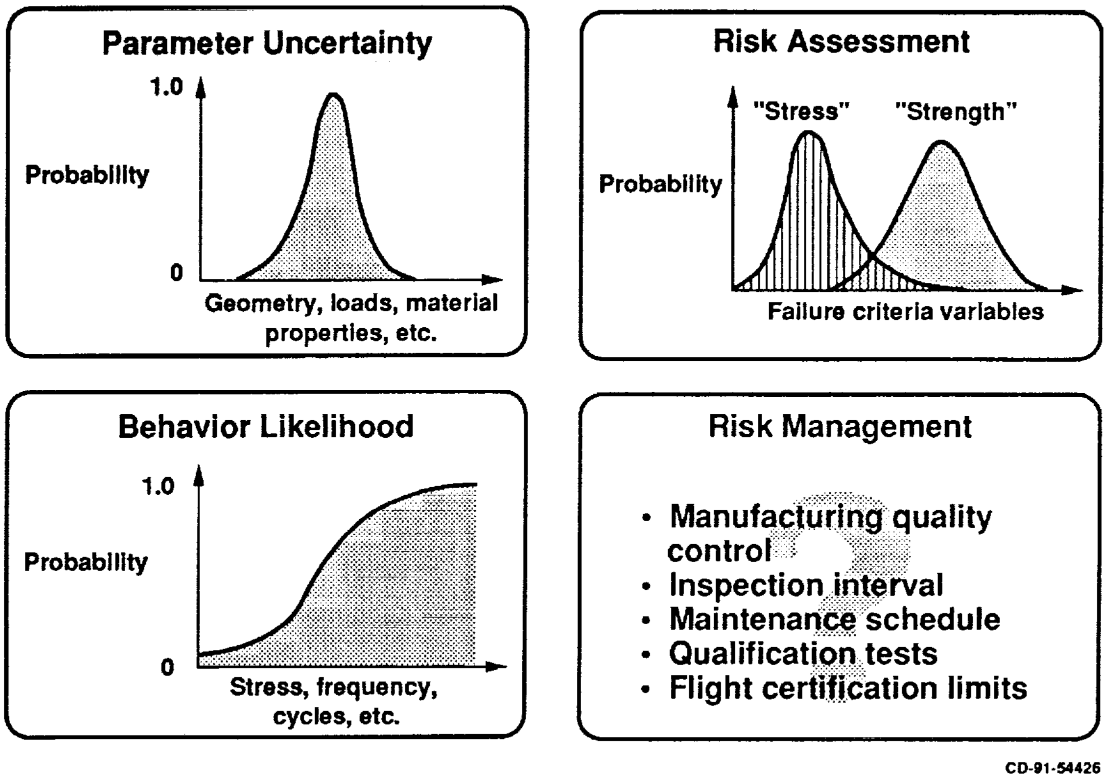
The thermomechanical performance and structural integrity of intermetallic and ceramic matrix composites in high-temperature engine applications are governed by the behavior of the constituent materials. Local influences which can affect the behavior of a structural component are caused by factors such as imperfect bonding and slipping at the fiber-matrix interface, a progressive damage and failure process induced by microcrack development in the typically brittle matrix materials, and constituent material properties which vary nonlinearly and may exhibit a cyclic history dependence over the range of operating conditions experienced by candidate engine components. For the analysis and design of engine components fabricated of these materials, it is desirable to account for the local factors and to relate their effects on the global structural performance. For this purpose, an integrated multiscale approach has been developed, as depicted in the figure. In the tradition of earlier approaches for polymeric and metallic matrix composites, the new capability incorporates (1) nonlinear constituent material models and failure models, (2) composite micromechanics and macromechanics models, and (3) finite-element global structural analysis models. The unique unit cell which serves as the basis of the micromechanics model allows an arbitrary level of resolution of locally nonuniform or discontinuous behavior of material properties, stress and strain, temperature, and other critical variables. Despite this capability for capturing local detail, the multiscale approach maintains a practical computational efficiency for realistic engine component analyses.

Probabilistic Analysis Methods Quantify Risk for Better Design Decisions

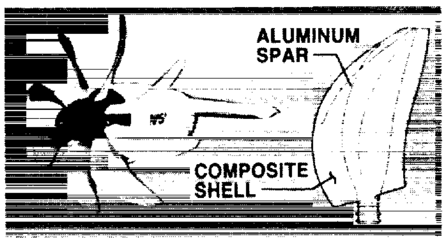


The variables of the structural design process, including geometry, material properties, loads, and boundary conditions, exist only with a certain degree of natural variability. The uncertainty of these variables contributes to an associated level of risk that the resulting design for a structural component will perform unexpectedly. The level of risk in a design is not directly quantified by the traditional deterministic design methodology. Rather, the deterministic design methodology devised the concept of the "safety factor" as a qualitative indicator of the risk in a design. This approach is inherently conservative and provides no basis to attain the desired balance between safety and efficiency of the design. A probabilistic analysis and design methodology, on the other hand, provides the formalism to quantify design uncertainty. As the figure implies, a probabilistic methodology establishes a rational basis for assessing risk and making risk management decisions. A probabilistic analysis and design methodology is especially pertinent in the design of high-performance, high energy-propulsion systems where mission economy and safety are the primary (and competing) design objectives. In this case, the ability to accurately quantify reliability and risk is essential to achieve an acceptable balance between performance and safety.

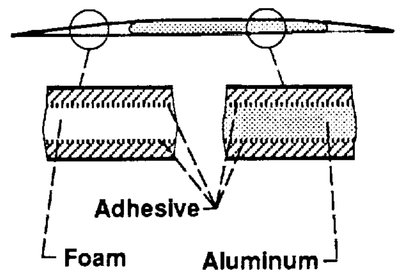
Structural Tailoring Resolves Complex Requirements for Optimum Design

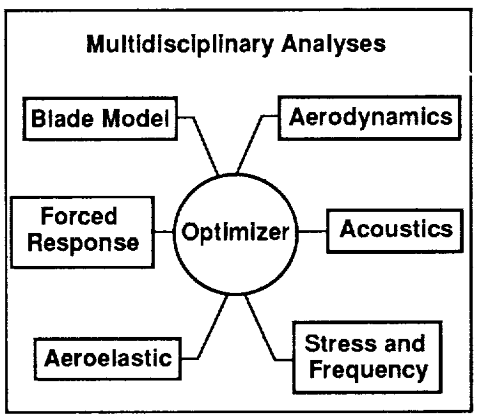
Advanced Propfans: Complex Geometry and Construction

Turboprop Stage and Propeller



Blade Internal Structure



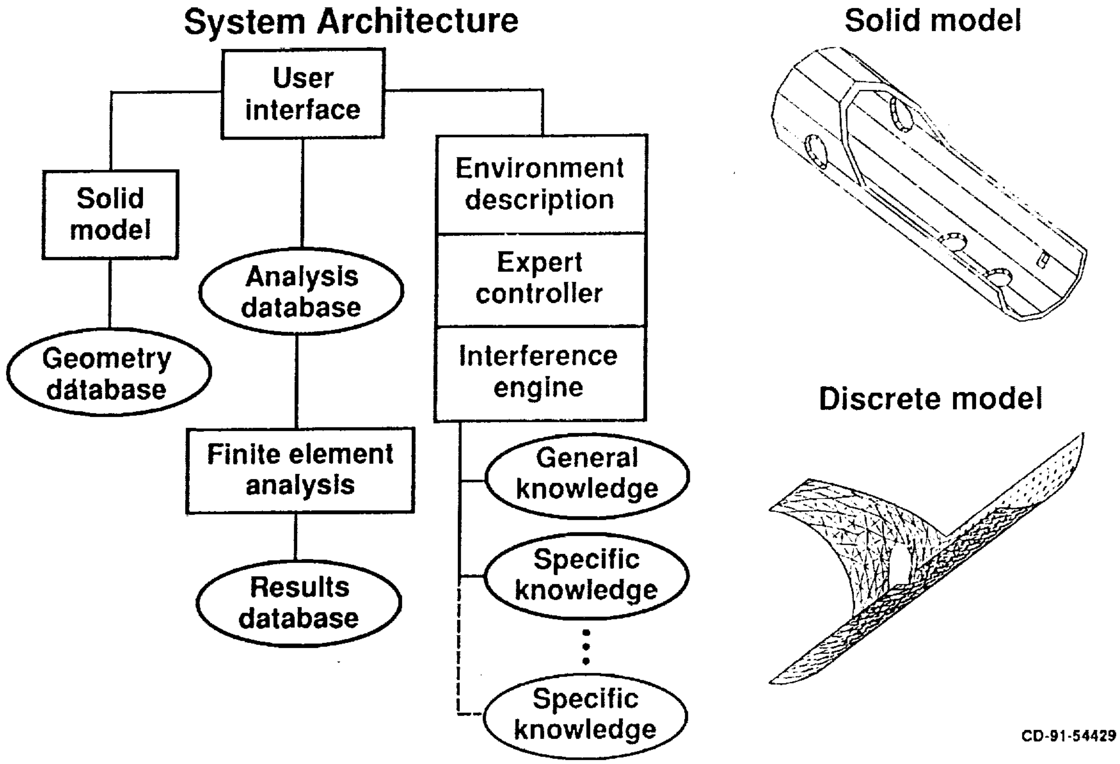


Propfan SR7 Optimization

	Initial design	Final design
Efficiency, %	82.86	83.17
Noise, dB	143.8	137.3
Weight, lb	41.1	41.2
Cost reduction, %		3.32

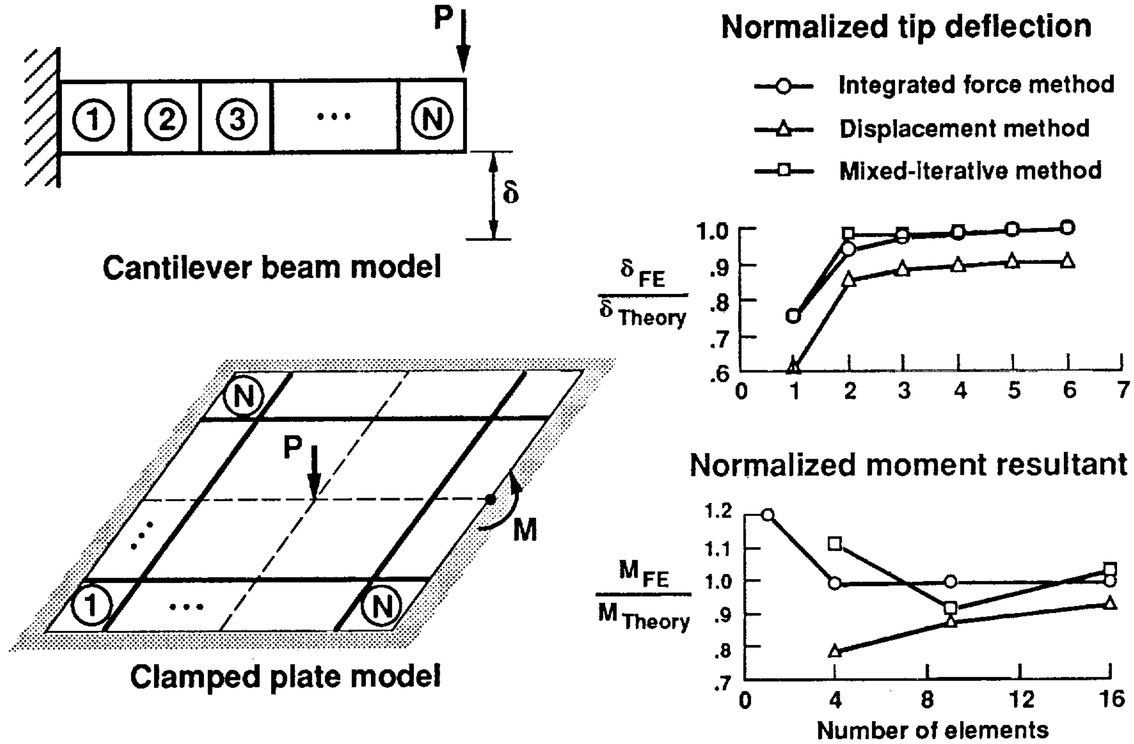
The traditional approach to engine component design has been to satisfy competing multidisciplinary requirements independently through manual design iterations. This process, which is usually conducted between several discipline-specific groups, inherently becomes time consuming and expensive, cumbersome and error-prone, and highly subjective. The typical process, therefore, can be carried out only to the point where a satisfactory design is achieved. The luxury of continuing the process to find the best design is virtually never afforded. Particularly relevant examples of this design scenario occur in the case of engine blades. Recent development of the advanced turboprop propulsion concept presents a consummate example of the ponderous task of trying to satisfy multidisciplinary design requirements. The design of advanced propfan blades presented the opportunity to demonstrate an alternative strategy. The approach taken was to streamline, automate, and formalize the propfan design process by incorporating the multiple discipline-specific analyses together with numerical optimization techniques into a computationally effective design-tailoring system. As summarized in the figure, the design-tailoring strategy proved to be highly successful for the propfan application. The concept of component-specific design tailoring has been successfully extended to cooled turbine blade applications and, most recently, a cooled wall panel structure for hypersonic engine inlets.

Expert Systems Capture Heuristic Knowledge To Guide Structural Modeling and Analysis



The creation of geometric and discrete models of structural components for analysis by the predominant finite-element method remains a subjective process that relies to a great extent on the experience and judgement of the structural engineer. Of considerable interest is the notion of capturing the heuristic reasoning and knowledge that constitutes the structural design process. The potential benefit of such a concept is to enable less experienced engineers to consistently create more effective models and achieve more reliable analyses. The ability to configure an "advisor" for structural modeling and analysis has been demonstrated recently with the development of the automated design expert (ADEPT) system. The ADEPT system combines solid- and discrete-model-creation facilities with an expert system that embodies knowledge pertaining to the assumptions and methodology of finite-element structural analysis. The ADEPT system guides the engineer through an examination of various features of the component model including geometric attributes and loading and boundary conditions. The ADEPT system makes recommendations for creating the appropriate and most effective discrete model for subsequent solution using specific finite-element analysis application programs. As the figure illustrates, the feasibility of a specialized expert system such as ADEPT for assisting engineers in the structural modeling and analysis process has been demonstrated for complex configurations typical of engine components.

Advanced Finite-Element Methods Provide More Effective Structural Analyses



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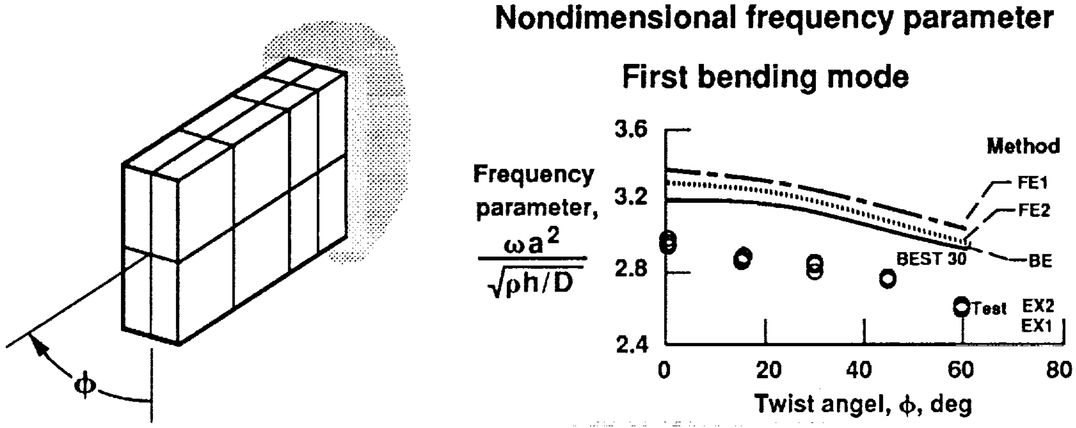
Reliable and cost-effective engine component design requires accurate and efficient structural analysis tools. The finite-element method is clearly the predominant tool utilized today for the analysis of complex structures in general. Furthermore, the overwhelming majority of production-level, finite-element-application programs are based on the conventional "displacement" or "stiffness" method concept which originated over thirty years ago. Despite this prominence, the displacement-based, finite-element method exhibits deficiencies particularly in its ability to resolve internal force and stress fields. These limitations generally require the utilization of very dense finite element models with many degrees-of-freedom to adequately resolve the important field quantities. The penalty associated with this is manifested in both the person-time to create the model, the computational resources to conduct the analysis, and the difficulty of assessing the quality of the analysis results. Two new formulations for finite-element analysis are being developed (the mixed-iterative method and the integrated-force method) in the attempt to alleviate the shortcomings of the displacement method. The results presented in the figure are for simple test cases that have recently been investigated to examine the potential benefits of the new methods. As seen in the results, the new methods appear to provide more accurate representations of both displacement and stress fields with sparser models. This advantage is more significant for the larger models of real engine components.

Advanced Boundary–Element Methods Provide a Viable Alternative For Structural Analyses



Result designator	Description
FE1	Finite-element shell model (294 DOF)
FE2	Finite-element solid model (660 DOF)
BE	Boundary-element model (288 DOF)
EX1	NASA experimental data
EX2	AF experimental data

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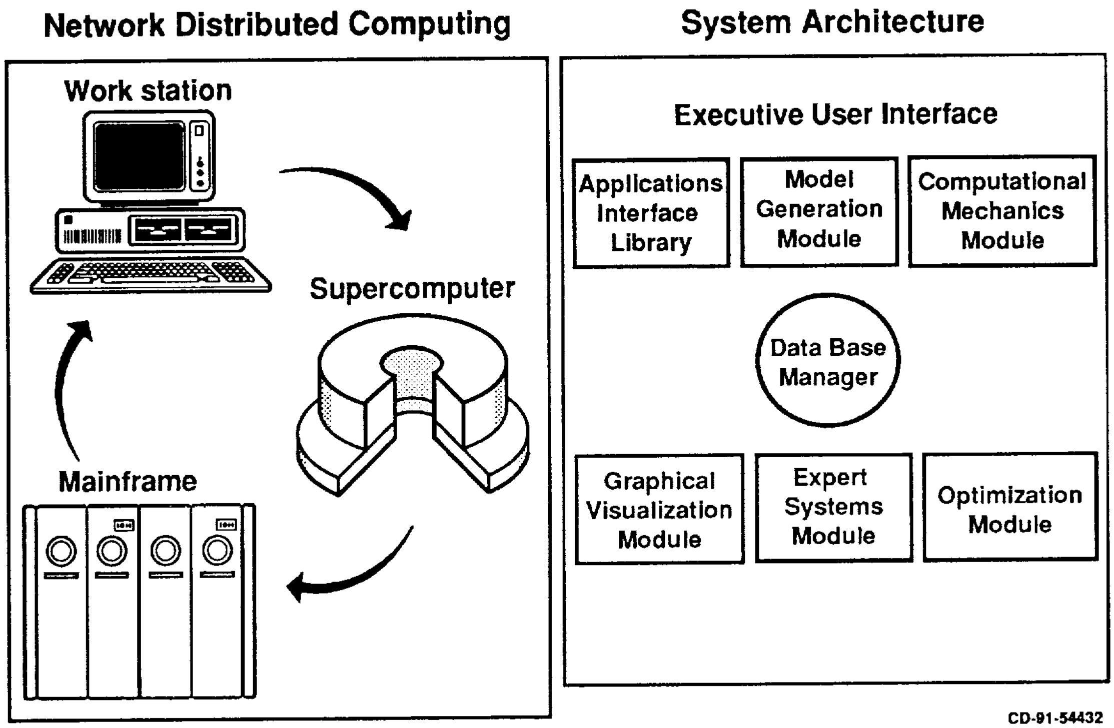
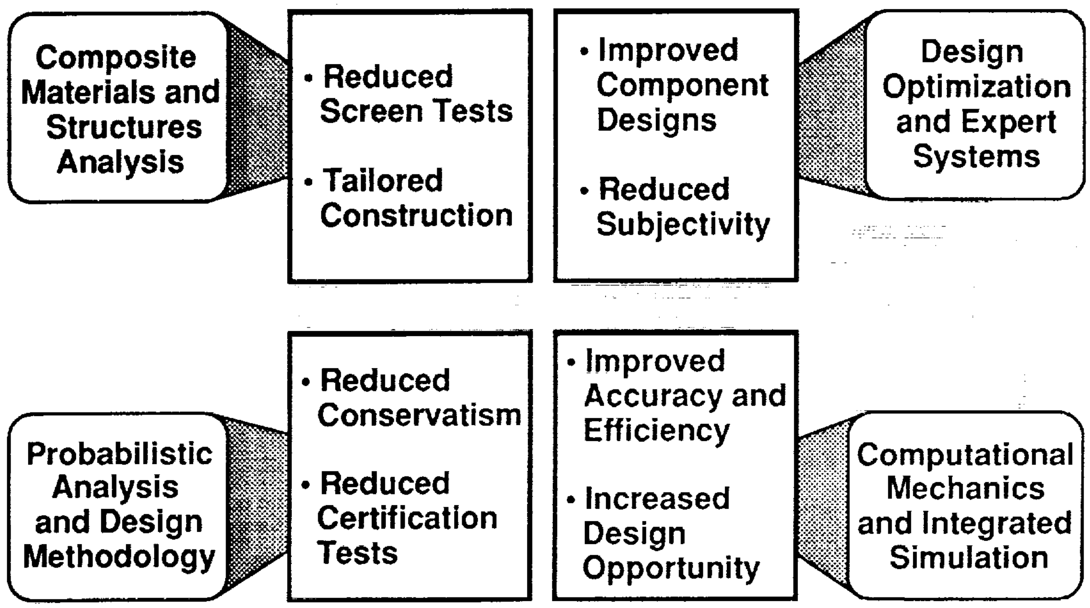
Although the boundary-element method has been recognized for nearly as long as the more prominent finite-element method, it has been given negligible development effort and, therefore, has had limited utility as a structural analysis tool. The fundamental advantage that the boundary-element method possesses is that, for certain types of problems, it requires the discretization of only the bounding surface of a structure and not the complete domain. This fundamental advantage, unfortunately, extended only to a very restricted class of problems for which the fundamental integral representation contained no domain components. It is because of the early perception that boundary-element methods would never have as general a utility as finite-element methods that it received such scanty attention until only recently. Concerted efforts have been made in the last several years to extend the viability of the boundary-element method to a much broader range of problems. The focus of these efforts has been to contend with the special circumstances faced in engine component analyses, including complex geometry, anisotropic materials with history-dependent inelastic behavior, cyclic loading, and heterogeneous boundary-conditions, etc. These efforts have culminated in a comprehensive and general-purpose boundary-element structural analysis tool. The capabilities provided by this tool give the engineer a significant new alternative for structural analysis to supplement the existing arsenal of finite-element tools. As illustrated by the example results given in the figure, the boundary-element method has gained a new superiority for solving a broader range of engine structural analysis problems.

The Engine Structures Simulator—A Unified System For Adaptive Analysis and Design



The Engine Structures Computational Simulation project has the objective to investigate, develop, and implement the required technologies to enable the simulation and synthesis of engine systems structural performance. *Engine structure* is used in the general context and refers to any extent of the engine which is of interest. This can range from a subcomponent (airfoil) to a component (blade), an assembly (rotor), a subsystem (compressor), or the complete system (turbofan engine). *Structural performance* refers to any behavior parameter or measure of merit such as stress or strain, vibration frequency, life expectancy, weight, reliability level, or cost. The concept herein of *simulation* implies a continuous process that permits creation and evaluation of engine structural performance models as an adaptive and continuous process. The simulation process should permit simultaneous models of varying fidelity and solution of those models with arbitrarily specified resolution. The principle end product of the project is a computational system (Simulator) which embodies the strategy and capacity to perform the diverse tasks that comprise the simulation process. This *computational system* represents the synergism of computational mechanics methodology and computer software and hardware implementation. It follows that the Simulator is a comprehensive entity encompassing aspects of model generation, computational mechanics, information management, graphical visualization, simulation process control, software system engineering, distributed computing, and so on. Providing the engine structural simulation capability envisioned demands unprecedented utility, flexibility, and adaptability within a unified framework.

Computational Structures Technology Can Significantly Enhance Future Propulsion Systems



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This presentation gives a partial overview of research underway in the Structures Division of Lewis Research Center, which collectively can be referred to as the computational structures technology program. The accomplishments anticipated in this program will generally expand the benefits of computational simulation far beyond the capability of today's analysis and design practice. To be more specific, some expected benefits from each of the four major categories discussed are

(1) *composite materials and structures* - reduced requirements for candidate composite material screening tests and new opportunities for tailored material and structural design

(2) *probabilistic analysis and design methods* - reduced design conservatism and reduced requirements for hardware certification tests

(3) *design optimization and expert systems* - improved component designs and reduced subjectivity of the design process with more consistent success

(4) *computational methods and integrated simulation* - improved accuracy and efficiency for structural analysis and expanded design opportunities to examine alternative concepts and to address issues that have previously been confronted only through expensive and time-consuming hardware tests